# Analysis of Automated Aircraft Conflict Resolution and Weather Avoidance

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**This paper describes an analysis of using trajectory-based automation to resolve both aircraft and weather constraints for near-term air traffic management decision making. The auto resolution algorithm developed and tested at NASA-Ames to resolve aircraft to aircraft conflicts has been modified to mitigate convective weather constraints. Modifications include adding information about the size of a gap between weather constraints to the routing solution. Routes that traverse gaps that are smaller than a specific size are not used. An evaluation of the performance of the modified autoresolver to resolve both conflicts with aircraft and weather was performed. Integration with the Center-TRACON Traffic Management System was completed to evaluate the effect of weather routing on schedule delays.**

## I. Introduction

THE Federal Aviation Administration (FAA) is currently handling nearly 120,000 flights a day through its Air Traffic Management (ATM) system[i] and air traffic congestion is expected to increase substantially over the next 20 years[ii]. Weather-induced impacts account for 70% of all delays with convective weather accounting for 60% of all weather related delays[iii]. To improve ATM decisions in all weather conditions, weather information must not only be integrated with decision support algorithms but those data need to be translated into impact on the ATM system to create advisories to avoid regions where pilots are likely not to fly. The Convective Weather Avoidance Model (CWAM)[iv] has been integrated with the Center-TRACON Automation System (CTAS) for improved automated decision making in the presence of convective weather. CWAM translates convective weather information to ATM impact by identifying convective regions of airspace pilots are likely to deviate around as well as regions they may fly through. This model will help minimize lost capacity due to convection by providing more accurate regions where an aircraft re-route is required. Previous work by McNally and Thipphavong evaluated the autoresolver without weather constraints. More recent work by Karahan et al[v]., evaluates the ability of the autoresolver implementation in the Airspace Concept Evaluation System to solve weather conflicts only. This work extends the work conducted by McNally and Thippavong by using the same autoresolver logic

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with modifications to also solve weather conflicts and evaluates the delays incurred by weather routing using the CTAS Traffic Management Advisor.

This study uses an automatic conflict resolution algorithm developed and evaluated at NASA Ames[vi,vii,viii,ix,x] and implemented in CTAS was modified to also handle convective weather constraints. Modifications to this algorithm include the use of a direct-to advisory to a downstream meterfix which is currently implemented in the Airspace Concept Evaluation Tool developed at NASA-Ames[xi]. To solve aircraft conflicts with weather constraints, a direct-to a downstream meter fix will be considered first. If that solution cannot find a path that avoids both the weather constraint and aircraft, the automated conflict resolution logic designed to solve aircraft to aircraft conflicts will be used. Another enhancement to the autoresolver is to evaluate the size of gaps between weather constraints to evaluate if those gaps are likely to be traversed by a pilot. Additionally, the weather routing advisory was integrated with the CTAS Traffic Management Advisor (TMA) to evaluate the delays from aircraft re-routing.

This paper presents a description of the CWAM model, the automatic conflict-resolver logic and how it was modified to include weather routing, and the Traffic Management Advisor. Following is a description of this experiment that focused on the en-route airspace over Indianapolis Center. A results and analysis section describes the analysis methodology and discusses the effectiveness of this algorithm to solve both aircraft and weather conflicts. Next is a discussion of how the resolutions affect TMA schedule times. The paper ends with conclusions and suggestions for future work to improve tactical aircraft routing considering weather constraints.

## II. The Convective Weather Avoidance Model

The following description of the CWAM is found in DeLaura and Evans, 2006. The CWAM developed at MIT/Lincoln Laboratory translates convective weather information to ATM capacity to help reduce the impact of convective weather-constrained regions on ATM performance. It challenges the notion that all pilots adhere to the FAA Aeronautical Information Manual guidelines that recommend pilots avoid thunderstorms characterized as severe of by an "intense radar echo" in en route airspace by at least 20 nautical miles (40 km).[xii] CWAM translates convective weather information to ATM impact by not only predicting convective regions pilots are likely to deviate around, but in some cases, regions they will fly through. This type of meteorological information translation should be performed for all weather data as ATM decisions using meteorological information should be less concerned with what the information reveals about the state of the atmosphere and more concerned with how that information translates to ATM impact.

CWAM is based on the analysis of approximately 500 en route flight trajectories through a single Air Route Traffic Control Center (ARTCC) from five different days in 2003 with significant convective weather. Ground speed and altitude from each Enhanced Traffic Management System (ETMS) flight trajectory were used to interpolate a corresponding planned trajectory that followed the flight plan recorded in the ETMS data. Weather encounters were identified along the planned trajectory, and each encounter was classified as a deviation or non-deviation, based on the mean distance between the planned and actual trajectory over the course of the encounter. The distance threshold used to classify deviations was derived from the analysis of approximately 500 actual and planned flight trajectories from a 24-hour period of clear weather.

The weather characteristics encountered along each planned trajectory provide a set of possible weather-related deviation predictors. Deviation predictors were defined from the Vertically Integrated Liquid (VIL), echo top and lightning fields using different statistical measurements (90$^{th}$ percentile, median, area coverage, etc.) from different route width scales (16 and 60 km wide routes, centered on the planned trajectory). VIL is the amount of liquid water that the radar detects in a vertical column of the atmosphere and is used to determine the severity of convection. High values are associated with strong convection that can be accompanied with heavy rain or hail. Echo top is the radar observed height of a convective system. The predictor sets, along with the deviation classifications, provided the inputs to the Gaussian classification algorithm. The algorithm identified the predictors that resulted in the smallest deviation classification errors and the bounding surface (in multi-dimensional predictor space) between deviations and non-deviations. The probability of deviation, as a function of the best predictors, was defined using the observed deviation statistics.

DeLaura and Evans in 2006 found that the difference between flight altitude and the radar echo top was the most accurate predictor of aircraft deviation around convective weather, with precipitation intensity playing a secondary role. Using the CWAM model, one can calculate weather avoidance contours that are a function of echo top height and precipitation intensity. Figure 1 shows a scatterplot of weather-encountering trajectories from this CWAM study and depicts the deviation prediction model boundary between deviations (gold) and non-deviations (red). In this figure, trajectory points whose fill matches the background color represent correct deviation predictions (e.g., gold boxes in the deviation half-plane); points whose fill is different from the background (e.g., red boxes in the deviation region) represent prediction errors. The predictors are represented on the scatterplot axes. The X-axis is the percentage of pixels that exhibit at least level 3 VIL in a 60 km wide neighborhood centered on the trajectory. The Y-axis is the difference between flight altitude and echo top height, where the echo top height is measured as the 90$^{th}$ percentile in a 16 km wide neighborhood centered on the trajectory. The horizontal black line indicates echo tops at flight altitude; points above this line represent en route flights that flew over the echo tops.

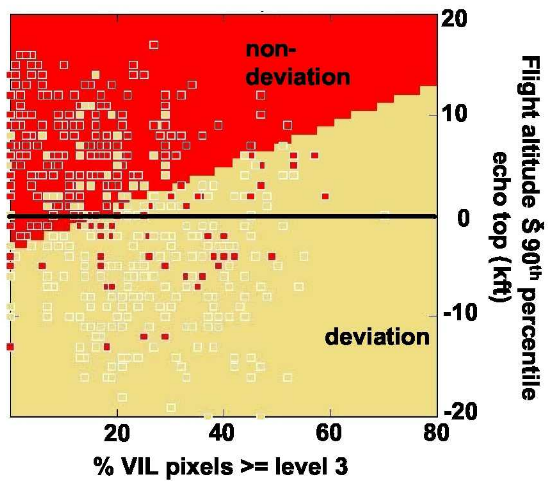



**Figure 1. Scattering of deviations and non-deviations from CWAM1 study.**

The probabilities of deviation computed by the CWAM are based on information from the Corridor Integrated Weather System (CIWS).[xiii] CIWS, created by MIT/Lincoln Laboratory, provides 2-hour convective forecasts updated every 5 minutes with 5-minute forecast time-steps. For example, a 2hr forecast produced at 1200Z will contain observed data for 1200Z and predictions for 1205Z, 1210Z, 1215Z, etc. CWAM creates Weather Avoidance Fields (WAF) in the form of polygons. These are computed at the same temporal resolution as the CIWS data for altitudes ranging from 24,000 ft to 44,000 ft at 1,000 ft increments. Figure 2 shows CIWS echo top and VIL data in FACET represented as contour plots. Figure 3 shows WAF deviation probability contours computed using these CIWS data for 25,000 ft and 32,000 ft. The contours represent probability of deviation. At the bottom right corner, below the data is the forecast time and altitude of the CWAM prediction.. Date, GMT time are shown in the lower right corner of each figure. Below that is the forecast time of the CIWS data used to compute these WAF contours. The altitude of the WAF is shown next to that forecast time. In Fig. 3, the forecast time is 0 min indicating these WAF data are not based on any forecasts but on observations of CIWS data. Subsequent CWAM models have been developed but are not used in this study[xiv].

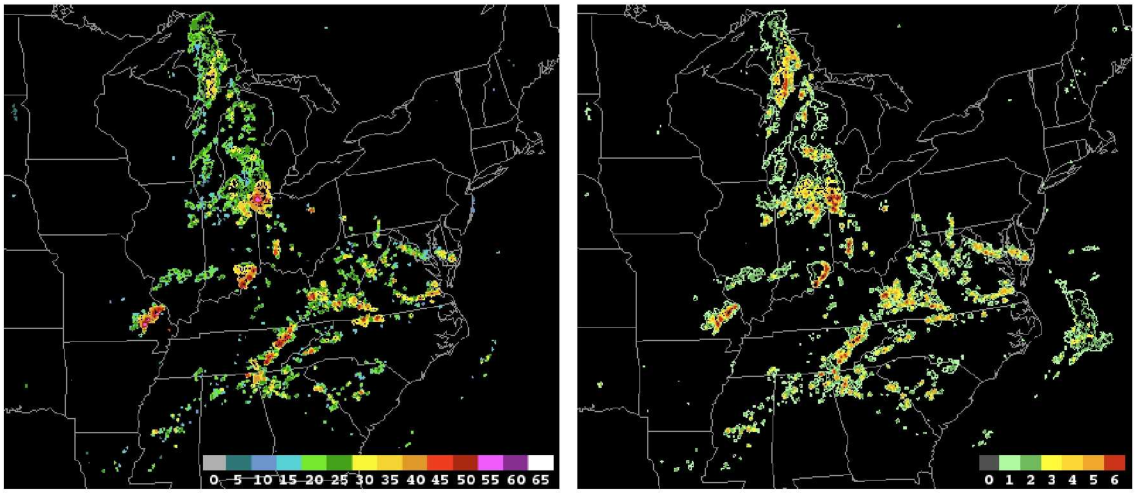



**Figure 2. CIWS echo top (left) and VIL (right). Echo top values in the legend are in 1000's ft. VIL values 0 – 6 are shown in the legend in the figure on the right.**

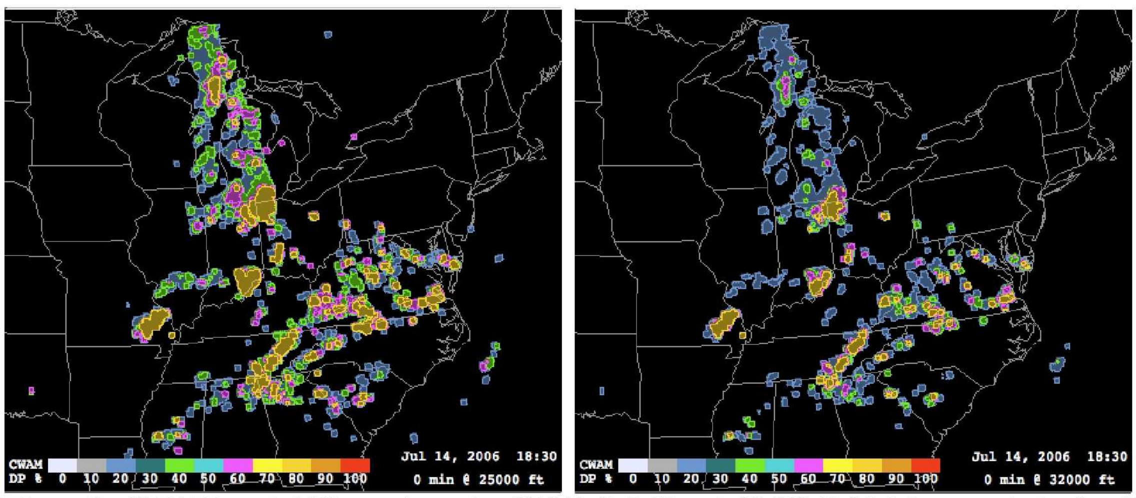



**Figure 3. CWAM probability contours for 25,000 ft (left) and 32,000 ft (right) computed using the CIWS data in Fig. 2.**

## III. The Traffic Management Advisor

TMA is a key ground-based technology for maximizing arrival throughput given airspace and airport capacity constraints. Within a single ARTCC, TMA calculates optimal aircraft sequences and schedules to the runway, TRACON meter fix and outer metering arcs (approximately 60 nmi from the runway) on a first-come-first-served basis[xv]. For the sector controller, the primary outputs of TMA for use in facilitating ERO in transition airspace are Scheduled Times-of-Arrival (STAs) at the TRACON-boundary meter fix. To calculate STAs, TMA first calculates Estimated Times-of-Arrival (ETAs) for each inbound aircraft to the meter fix using 4D trajectories predictions calculated by the CTAS Trajectory Synthesizer (TS). The TS use force-based equations-of-motion based on an idle-thrust engine setting assumption for jets, and nominal lift and drag models for each aircraft type. To generate spacing requirements at the meter fix, the TMA scheduler applies capacity restrictions for wake vortex separation, conflict avoidance and airport acceptance rate. In typical operations where demand exceeds capacity, spacing, sequencing and scheduling at the TRACON meter fix requires that delay be absorbed in transition airspace for most aircraft. It's important to note that today's TMA system only ensures that aircraft are conflict free at the meter fix itself, not at other points along any trajectory assumed to be flown in complying with the meter fix STA.

In current TMA operations, controllers receive TMA schedule information in the form of a metering list displaying STAs and required delay absorption at the outer arc and TRACON-boundary meter fixes. For a typical transition airspace region containing high and low altitude sectors, the high-altitude controller maneuvers aircraft to absorb any delay required prior to aircraft passing through the outer arc, while the low altitude controller is responsible for absorbing any remaining delay prior the aircraft crossing the TRACON meter fix.

## IV. The weather and aircraft conflict autoresolver

The auto-resolution algorithm described by Erzberger[5] to solve aircraft to aircraft conflicts uses procedures based on operational insights and examining how experts such as air traffic controllers resolve conflicts. His algorithm solves conflicts a pair at a time using three types of maneuvers. These maneuvers include changes in altitude, horizontal route and speed. The type of maneuver is determined by the type of conflict. Conflict resolutions are determined by conflicts between a combination of cruise, arrival and climbing aircraft. Erzberger shows a list of conflict maneuvers showing preferred maneuvers. These maneuvers are designed to minimize change in time from the original flight time. To solve a conflict, the conflict resolving logic will exhaust the list of conflict maneuvers for one aircraft before attempting to solve the conflict by maneuvering the other aircraft in the conflict. To exhaust the entire list for one aircraft requires the generation of 86 conflict resolution maneuvers.

For this study, the weather and aircraft avoidance logic is based on a two-tier system which has already been implemented in the . The first resolution method is based on using a direct-to advisory as described by McNally et al[xvi]. According to McNally, controller acceptance of the direct-to tool and its advisories were high. This work extends the use of direct-to advisories to solve both aircraft and weather conflicts as they are likely to be accepted by both controllers and pilots.

The second resolution method is based on the auto-resolver logic used to solve aircraft and aircraft conflicts with the additional constraint of solving weather conflicts. Weather constraints are described by CWAM WAF polygons that are defined in both time and space. The avoidance logic is the same for the aircraft to aircraft resolutions with the additional constraint of having to avoid WAF polygons of 80% deviation probability. The predicted aircraft trajectories are time-synchronized with the WAF to provide a architecture that can be used for longer range weather avoidance logic that depend on capturing dynamically changing weather phenomena. Once a maneuver has been computed, the resultant trajectory is tested to see if the new route intersects a specific WAF polygon. If it does, then another maneuver is used and tested again.

Modifications to the autoresolver include considering the size of gaps between weather cells. Figure 4 shows a probability distribution of aircraft and the gaps between WAF that an aircraft is likely to fly in between. Defining gaps or lanes around areas of convection was previously discussed by Mitchell et al[xvii]. In that work, they describe a method to create lanes of a specific width though a field of weather constraints to be used for capacity estimation of a region of airspace. The WAF used were contours of 80% deviation probability used observed WAF synchronized with aircraft position. The figure shows a majority of the aircraft flew between gaps for about 20nmi. Using these and other similar data, a minimum gap between storms can be identified that pilots not likely to traverse and routes through them can be removed from a routing solution.

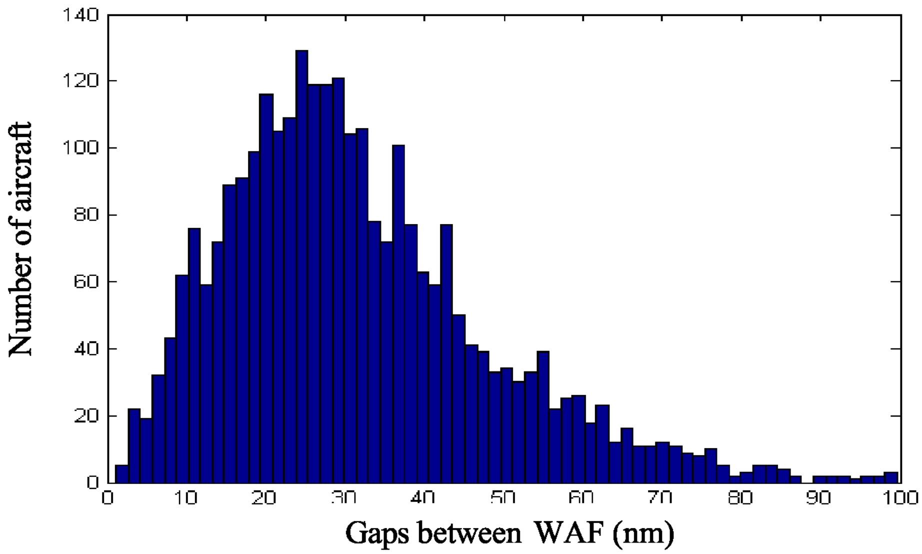



Figure 4. Size of gaps between 80% WAF that aircraft were observed to be flying inbetween.

## IV. Method

For this study, eight hours aircraft track data were used over the Indianapolis Center (ZID) for three different weather scenarios. The weather scenarios were varying amount of convective weather. These days were June 19, 2007 (bad), June 13th, 2007 (med), and July 24th, 2007 (good). ZID was chosen as it is covered by the CIWS data. Figures 5 through 7 show the radar reflectivity data from those days. A baseline dataset was created by running the eight hours of data without any CWAM data. The same dataset were re-run with WAF. The autoresolver would solve aircraft with aircraft conflicts while avoiding intersecting any WAF equal to or greater than 80%. Data for both runs were collected and compared. TMA delay times to the ZID were also archived for evaluation of delay due to conflict avoidance with WAF and aircraft.

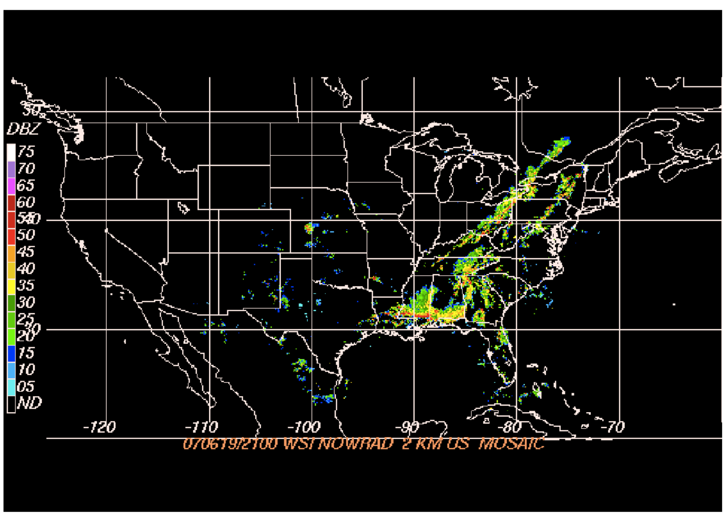



Figure 5. June 19, 2007 2100Z radar reflectivity image “Bad weather day”.

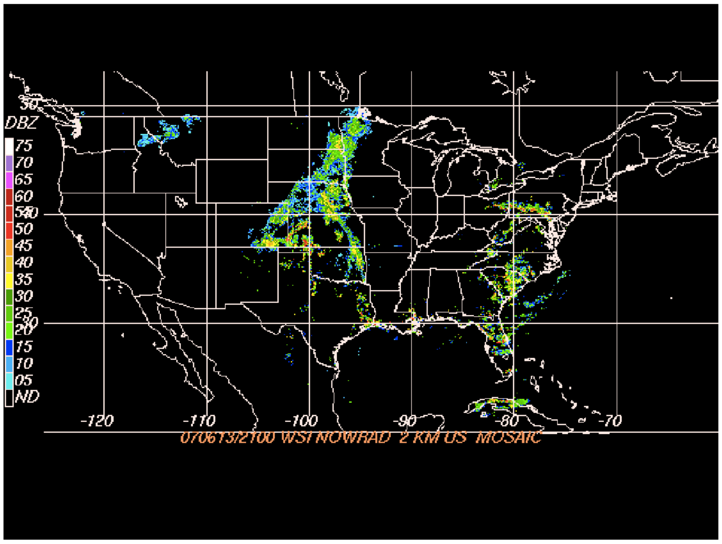



Figure 6. June 13, 2007 2100Z radar reflectivity image. "Medium weather day"

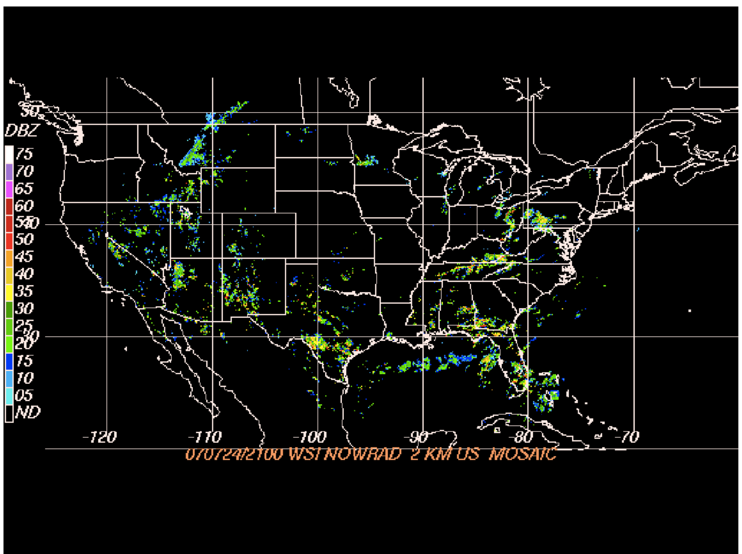



Figure 7. July 24th, 2007 radar reflectivity image "Good weather day"

## V. Results

The autoresolver is able to resolve both aircraft conflicts and regions of convective weather as depicted as WAF. Figure 8 shows a time-series of a typical weather conflict avoidance maneuver that is conflict free of weather and aircraft up to 20mins from the current position of the aircraft. Figure 7a shows the original aircraft conflict with the WAF as shown by the green flight plan path. The aircraft is flying west to east. High altitude sectors of ZID are shown as brown outlines. The flight data block of the aircraft is shown with altitude, ground speed, callsign and aircraft type. Altitude is in hundreds of feet and ground speed is in knots. WAF probability legend is shown at the bottom right. Figure 8b shows the resolution path to avoid the WAF and Fig. 8c shows the aircraft following the resolution.

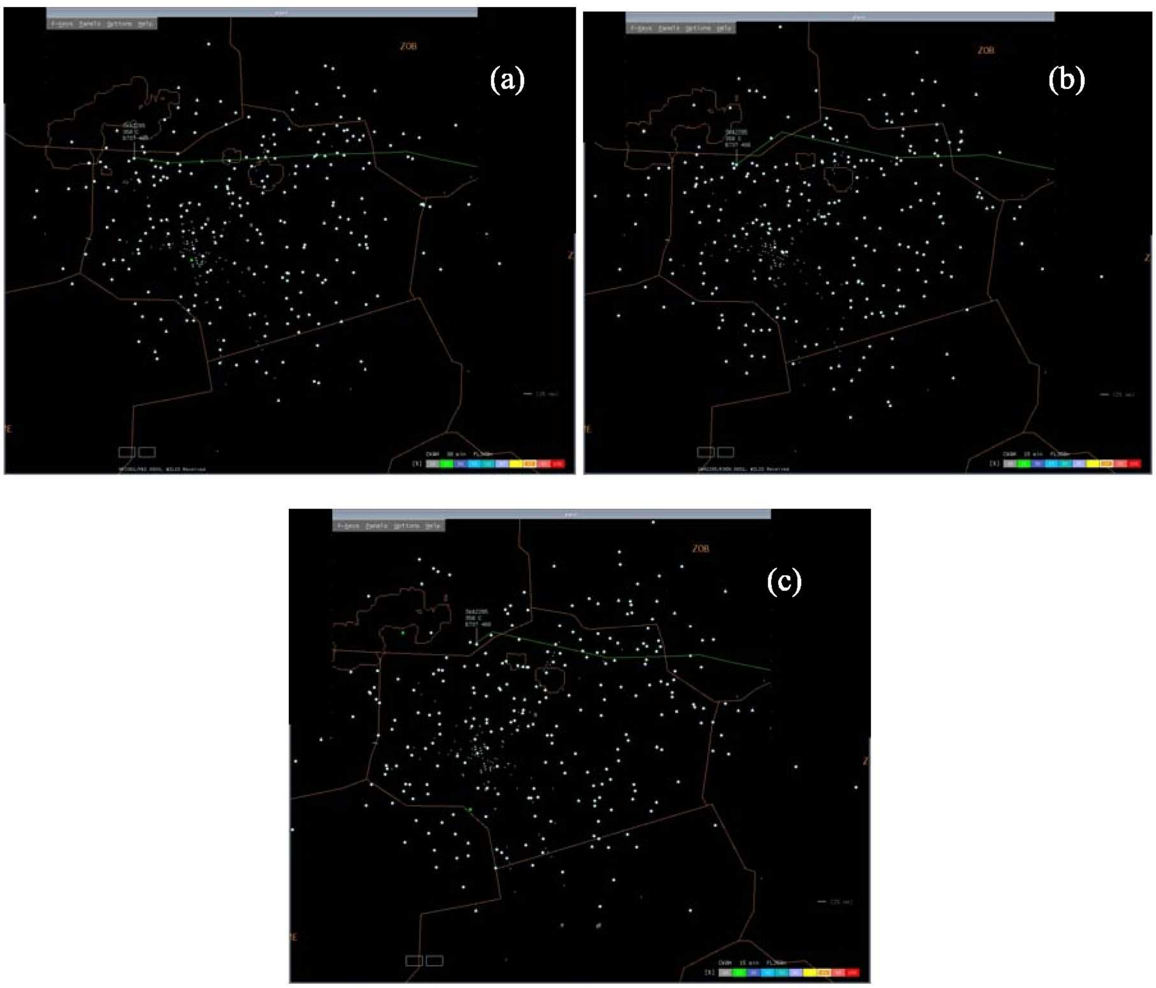



**Figure 8. Aircraft automatically avoiding WAF fields of 80%. Green line is the aircraft flight plan. Legend shows WAF probabilities. Aircraft datablock shows callsign, current altitude in hundreds of feet, aircraft type and ground speed.**

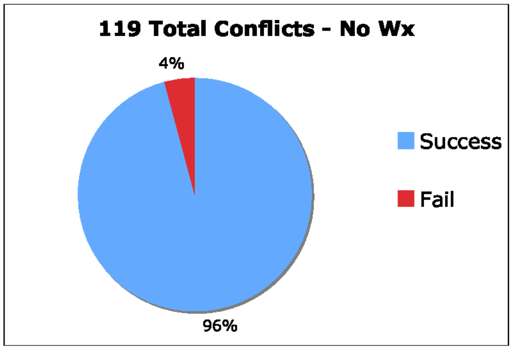



Figure 9. Good weather day, aircraft to aircraft only, conflict resolutions

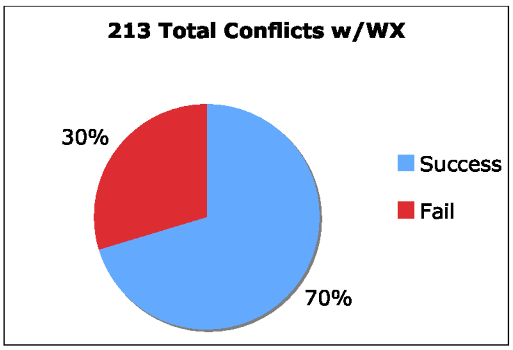



Figure 10. Bad weather day showing success rate of conflict resolutions

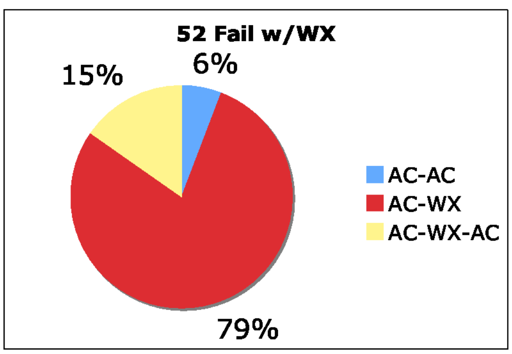



Figure 11. Breakdown of failed resolutions by conflict type.

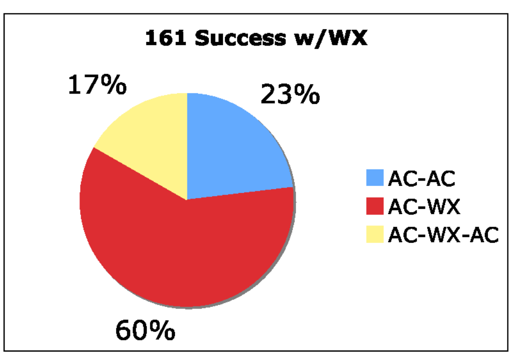
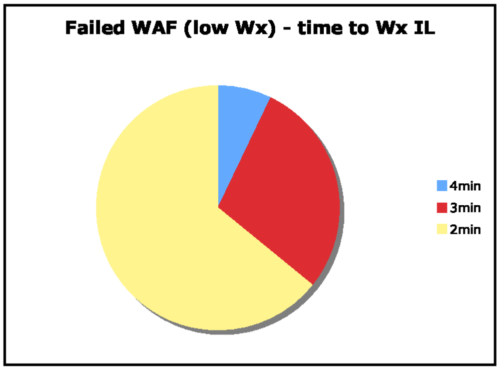



Figure 12. Breakdown of successful resolution by conflict type.



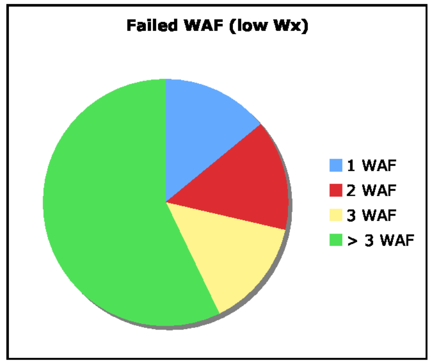




Figure Placeholder for TMA delay data.

Figure 9 shows there were 119 aircraft to aircraft conflicts detected in CTAS over the two hour period. During this simulation, all flight tracks were assumed to be for a non convective weather day. The number of unresolved aircraft conflicts was 5 which resulted in a 4 percent failure rate, a typical number for the autoresolver.

Figure 10 shows the same aircraft flight plans simulated with the June 19 "bad" weather day data. The autoresolver treated the intersection of the aircraft flight track with a weather avoidance field from the CWAM as an intersection with another aircraft and the conflict pair was sent to the autoresolver. For conflicts involving weather, the autoresolver had the additional constraint that could only change the path of the actual aircraft. In the data of Figure 9, the autoresolver could maneuver either aircraft to resolve the conflict. Resolutions that resulted in conflict with other aircraft or another weather avoidance field were rejected. It is noted that given the exact same traffic pattern through the ZID center, weather increased the total number of conflicts by 79 percent. The successful resolutions decreased from 96 to 70 percent. The total number of aircraft to aircraft conflicts actually decreased to 40 compared to the 119 from the no convective weather day. The total number of weather conflicts was 173.

Figure 11 shows a breakdown of 52 conflicts without successful resolutions. Table 1 show the individual categories. The majority of the failures were aircraft to weather with 41 of the conflicts unresolved or 79 percent. The next unresolved category was aircraft conflicts with weather and one other aircraft within the 20 minute tactical time horizon. Only eight out of 27 conflicts were unresolved. Three aircraft to aircraft conflicts were not resolved giving a rate of 6 percent, which is similar to the no convective weather day.

Table 1. Results of Two Hour Traffic and Weather Simulation in ZID

| | Fail | Fail, percent | Success | Success, percent |
|---|---|---|---|---|
| A/C to WX | 41 | 78.8% | 97 | 60.2% |
| A/C-WX-A/C | 8 | 15.4% | 27 | 16.7% |
| A/C to A/C | 3 | 5.7% | 37 | 22.9% |
| TOTAL | 52 | 30% | 161 | 70% |

Figure 12 shows the breakdown of successful conflict resolutions. Of the 161 successful resolutions, 60 percent were aircraft with weather, 15% aircraft to aircraft.

Future data will show the scheduling effect of the rerouting the aircraft around the weather using the Traffic Management Advisor Module in CTAS.

## V. Conclusions

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